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Spin Evolution of Neutron Stars in Binary Systems

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Abstract. I review our understanding of the evolution of the spin periods of neutron stars in binary stellar systems, from their birth as fast, spin-powered pulsars, through their middle life as accretion-powered pulsars, upto their recycling or "rebirth" as spin-powered pulsars with relatively low magnetic fields and fast rotation. I discuss how the newborn neutron star is spun down by electromagnetic and "propeller" torques, until accretion of matter from the companion star begins, and the neutron star becomes an accretion- powered X-ray pulsar. Detailed observations of massive radio pulsar binaries like PSR 1259-63 will yield valuable information about this phase of initial spindown. I indicate how the spin of the neutron star then evolves under accretion torques during the subsequent phase as an accretion-powered pulsar. Finally, I describe how the neutron star is spun up to short periods again during the subsequent phase of recycling, with the accompanying reduction in the stellar magnetic field, the origins of which are still not completely understood.

1. Introduction

We are primarily discussing spin-powered pulsars in this symposium: according to our current understanding of the origin and evolution of neutron stars in binary systems (see van den Heuvel 1992, hereafter vdH92), such a neutron star can have two distinct phases as a spin-powered pulsar. The first phase is that of the newborn, fast-spinning neutron star with rather high magnetic field ($\sim 10^{11} - 10^{13}$ G), while the second one is that of the recycled, very fast-spinning neutron star with rather low magnetic field ($\sim 10^{8} - 10^{11}$ G). Connecting these phases is that part of the life of the neutron star during which it appears as an accretion-powered pulsar.

This paper is a brief review of the processes that determine the evolution of the spin-rate of the neutron star as it passes from the first spin-powered phase to the accretion-powered phase, and then on to the second spin-powered phase through recycling (see Ghosh 1994, hereafter G94). The passage from the first

Spin-powered phase to the accretion-powered phase occurs through a process of spindown of the neutron star by electromagnetic and plasma torques which I call “initial spindown” throughout this paper. In the accretion-powered phase of pulsed X-ray emission, the neutron star shows both spin-up and spindown under the action of accretion torques. Finally, the passage from accretion-powered phase to the second spin-powered phase, *i.e.*, recyclings, occurs through a process of massive (~ Eddington-rate) accretion, during which there is spin-up by accretion torques-called “final spinup” throughout this paper, followed by a termination of accretion. These processes are discussed in turn in the subsequent sections of this paper.

Spin evolution, and the above processes that cause it, are best studied on a Magnetic Field-Period ($B - P$) diagram of neutron stars, as shown in Fig.1. In addition to the “pulsar island” (which contains the bulk of those single neutron stars which are in a state analogous to that which I named “first spin-powered phase” above for neutron stars in binaries), the figure shows (a) the recycled pulsars at the bottom left of the diagram, *i.e.*, the second spin-powered phase of pulsars, (b) the X-ray pulsars at the top right of the diagram, *i.e..*, the accretion-powered phase of pulsars (only those X-ray pulsars for which a direct measurement of the magnetic field from the cyclotron line is available [see Nagase 1992] have been used here), and, (c) the two examples of binary neutron stars known at the present time which are in their first spin-powered phase, namely, PSR B1259-63 and PSR J0045-73 (Johnston *et al.* 1994, hereafter J94; Kaspi *et al.* 1994): we nave heard about these two massive radio binary pulsars in detail from Dr. Manchester in this symposium. Note that recycled neutron stars can be either binary or single: the processes that may disrupt the binary before the second spin-powered phase begins are. indicated in §4.

2. Initial Spindown

During this process, the neutron star moves to the right on the $B - P$ diagram on an approximately horizontal track. I consider the braking torques in turn.

2.1 *Electromagnetic Torque*

Electromagnetic braking torques are usually expressed in the form $N \propto \mu^2\ (\Omega_s/c)^3$, in analogy with the expression for magnetic dipole radiation in vacuum. Here, μ is the magnetic dipole moment of the star, and Ω_s is its angular velocity. This torque, which spins the pulsar down to a period P in $\sim 3.10^4 (P/50\ ms)^2 I_{45} \mu_{30}^{-2}$ yr, can brake the stellar spin to the critical point where plasma effects first dominate the torque. The critical period depends on the properties of the plasma flow from the companion to the neutron star: for mass capture at rates $\sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ from winds of speed $\sim 10^3\ \mathrm{km\ s}^{-1}$ from the companion, this period is $\sim 100\mu_{30}^{1/2}$ ms (Illarionov & Sunyaev 1975, hereafter IS). Here, I_{45} is the moment of inertia of the neutron star in units of 10^{45} gm cm^2, and μ_{30} is μ in units of 10^{30} G cm^3.

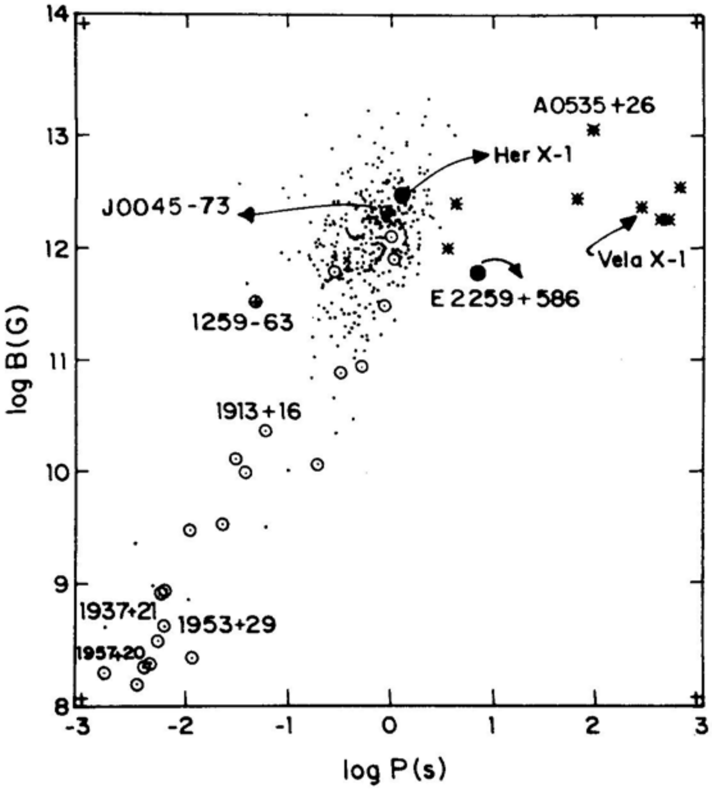

Figure 1: Spin and accretion-powerd pulsars on the B-P diagram. Dots indicate spin-powered pulsars, and stars, accretion-powered ones. Those spin-powered ones which are in binaries are encircled, and the two recently discovered massive radio pulsar binaries (PSRs B1259-63 and J0045-73) have an additional cross on their symbols. Some well-known pulsars are marked individually: these include (a) recycled pulsars, (b) PSR B1259-63, (c) two accretion-powered pulsars with relatively low-mass companions (Her X-1 and E 2259+586), and (d) one accretion-powered pulsar with a massive companion (Vela X-1).

2.2 *Propeller & Related Torques*

When the spin of the neutron star becomes slower than the above critical value, the dominant braking torques are those due to the deposition of energy and momentum into the matter (coming from the companion star) by the stresses associated with the magnetic field of the neutron star: these are the propeller-type torques. The scaling of the propeller torque was given in the original formulation (IS) as $N \propto (\mu^2/r_A^3)(\Omega_K(r_A)/\Omega_s)$, where r_A is the Alfvén radius and Ω_K is the Keplerian velocity. More detailed work (Mineshige *et al.* 1991; Davies & Pringle 1981; see

Henrichs 1983 for a review) on the plasma torques has shown since then that the most effective braking obtains at subsonic spin rates ($r_A\Omega_s < c_s$, c_s being the sound speed). This is the so-called subsonic propeller, the torque due to which scales as $\mu^2\Omega_s^2/GM$, independent of r_A. For supersonic propellers, the torque is smaller by a factor ~ ($c_s /\Omega_s\, r_A$), and reduces to the original IS scaling if $c_s \sim v_{ff}$ at r_A. Here, v_{ff} is the free-fall velocity. These braking torques, as well as some others described below, are listed in Table 1.

Table 1: Spindown Torques

Spindown Mechanism	Torque Scaling
Electromagnetic	$N \sim \mu^2(\Omega_s/c)^3$
Propeller: Original (IS)	$N \sim (\mu^2/r_A^3)(\Omega_K(r_A)/\Omega_s)$
Propeller: Subsonic	$N \sim \mu^2\Omega_s^2/GM$
Propeller: Supersonic	$N \sim (\mu^2\Omega_s^2/GM)(c_s/\Omega_s r_A)$
"Frictional" (Aligned Rotator)	$N \sim p\, r_A^3$
Compton-Heated Wind	$N \sim \dot{M}_{out}\ \Omega_s r_A^2$

I now mention two other types of braking torques that may be relevant in the initial spindown phase. First, note that the propeller effect, as originally concieved, requires a misalignment between the spin and magnetic axes of the neutron star. However, even when the two axes are aligned, there may be a significant "frictional" braking torque (Mineshige *et al.* 1991) on the star, which is expected to scale as $N \propto p\ r^3_A$, where p is the total pressure at r_A. This torque is therefore expected to operate simultaneously with all propeller-type torques. Second, it has been suggested recently (Illarionov & Kompaneets 1990) that the propeller mechanism "switches off" when the condition $\Omega_s > \Omega_K\ (r_A)$ is no longer satisfied. There is, instead; accretion to the star over some parts of the total cross-section, and outflow of a Compton-heated wind over the other parts, the resultant braking torque scaling as $M_{out}\,\Omega_s\, r^2_A$. Here, M_{out} is the mass outflow, rate.

For typical values of stellar and binary parameters, the plasma torques described above give timescales for spindown which are comparable to or shorter than that given above for the electromagnetic torque. It was therefore argued (Henrichs 1983) that the total duration of the initial spindown phase is essentially determined by the "bottleneck" of the elctromagnetic torque. However, this is true only if the different torques act *consecutively.* As I indicate below, this need not be the case in a highly eccentric binary system, such as PSR B1259 – 63, since, during each orbital cycle, elctromagnetic torques may dominate over those parts of the orbit where the plasma density is small, while plasma torques may dominate over those parts where the density is high, particularly near periastron. Then spindown would occur on a timescale which is an appropriate average of those due to the various torques acting over the orbital cycle, and which can be considerably shorter than that for electromagnetic braking alone.

2.3 *Spindown of PSR B1259-63*

Studies of the spindown history of PSR B125963, a neutron star-Be star binary with a highly eccentric ($e \simeq 0.87$) 3.4 yr orbit (J94), will map out the details of the processes of initial spindown. Far away from the periastron, the 47 ms pulsar undergoes spindown with a characteristic age of $3.3.10^5$ yr, predominantly by electromagnetic torques, which implies a magnetic field ~ $3.3.10^{11}G$ for the neutron star (J94). Close to periastron, plasma torques associated with the wind and the disk of the Be star contribute appreciably to spindown, and may even dominate it, depending on the relative dispositions of the orbital plane and the plane of the disk around the Be star. It is easy to show from Table 1 and the parameters given above that the timescales for spindown of this pulsar by the subsonic propeller torque and the supersonic (in the original IS formulation) propeller torque are approximately the same, and each is ~ 3.10^4 yr. The *instantaneous* spindown rate is, therefore, expected to go up by ~ an order of magnitude as the pulsar passes through the Be star's disk. How much enhancement this causes of the total spindown during periastron passage (*i.e.*, between the radio disappearance of the pulsar before periastron and its reappearance after periastron), which is the quantity actually observed, depends on the relative orientation referred to above (Ghosh 1994, in preparation). Naively, one expects the Be-star disk to be in the orbital plane, but this need not always be so, particularly for a young system such as PSR B1259-63. In fact, there are indications already that this is *not* the case here. First, there is little perturbation to the $H\alpha$ emission during periastron passage (Manchester 1994): this emission, which is thought to originate in the Be-star disk, is expected to be grossly perturbed by the tidal torques of the neutron star during periastron passage if the disk is coplanar with the orbit, as the detailed simulations of Kochanek (1993) have shown. Second, a coplanar disk would produce an orbital-phase-dependent perturbation in the spindown even relatively far away from periastron, for which there is little evidence at this point. Analysis of the radio observations of this system during the periastron passage of January 9, 1994, described by Dr. Manchester in an exciting talk in this symposium, will soon clarify this point.

2.4 *Braking by Onset of Disk Accretion*

At the onset of accretion to the neutron star from disks, or from stellar winds, the star is spun down further by the accretion torque. Here, I indicate how the braking torque acting at the onset of disk accretion is particularly effective in spinning down the star to $P \sim 100$ s (Elsner, Ghosh, & Lamb 1980, hereafter EGL).

The principal features of the accretion torque for disk accretion by magnetic neutron stars are summarized in §3.2. The torque spins the star down if the stellar spin rate, as measured by the dimensionless fastness parameter ω_s, exceeds a critical value ω_c, *i.e.*, the spin period is shorter than the critical value P_c which corresponds to the point $\omega_s = \omega_c$ where the accretion torque vanishes. Under the action of the braking torque, the star spins down from an initial period P_i to a final period $P_f \approx P_c$ in a time $\simeq$ $2.10^6\mu_{30}^{-2}$ $(P_f /100_s)^2(P_i / 1\ _s)^{-1}$ yr, if the accretion rate is a constant (EGL). If $\dot{M}$ goes through outbursts or flares, spindown can occur even more rapidly, as the braking torque can then continue to be very effective as the star spins down. In this way, the star can be spun down to a final period P_f from an initial period $P_i \ll P_f$ in a time as short as $1.5.10^5\ \mu_{30}^{-2}\ (\mathrm{P}_f\ /100_s)$ yr. Hence, this mechanism is clearly capable of producing the initial spindown to the long ($\gtrsim$ 100 s) periods, which ~ 45% of the known accretion-powered pulsars have, in a time which is short compared to the main-sequence lifetime of their companions(EGL).

3. Spin Evolution During the Accretion-Powered Pulsar Phase

For about half of the known (~ 35) accretion-powered pulsars, long-term period histories have been compiled from data collected over ~ 2 decades of satellite observation (for a review, see Ghosh 1994). From these compilations, the following (approximate) categories of secular trends in spin evolution have sometime been identified. First, there are those pulsars which have shown secular spin-up over essentially the entire stretch of observation (except possibly for a brief episode of standstill or slight spin-down), *e.g.*, Her X-l. Second, there are those which have, similarly, shown essentially secular spin-down, *e.g.*, 1E 1048.1-5937. Third are those which have shown considerable stretches of both spin-up and spindown, *e.g.,* A 0535+26, GX 1+4. Finally, there are those that seem to show “erratic” variation on these timescales, *e.g.,* X Per. It is quite possible, and indeed, rather likely, that such "different" categories are really manifestations of the same phenomenon, which is that all accretion-powered pulsars show intervals of spin-up and spindown when observed over sufficiently long periods of time. This is strongly suggested by the fact that one after another of these pulsars with a so called “pure” trend of either spin-up or spindown has shown a reversal of sign as the extent of the period history has become longer. One of the most recent examples of this is 4U 1626-67 (a 7.7 s pulsar with a very low-mass companion), which had been observed to spin up at almost a constant rate since its discovery in 1977, but is now observed by BATSE (see below) to be spinning down at a roughly comparable rate.

Recent observations by the Burst & Transient source Experiment (BATSE) on board the Compton Gamma-Ray Observatory have produced detailed period histories (see Ghosh 1994, and the individual references to BATSE work therein) of accretion-powered pulsars, accurately documenting changes on timescales which can be as short as ~ hours to days. This is to be contrasted with earlier X-ray satellite observations, which typically documented changes on timescales ~ months to years. BATSE observations have now provided detailed records of a phenomenon seen in earlier work, namely that spin-up/spin-down reversals on short timescales can occur even during a so-called “secular” phase of monotonic spin change on longer timescales.

These trends of spin evolution are interpreted in terms of accretion torques, whose characteristics are summarized below.

3.1 *Disk Accretion*

When well-developed accretion disks form (as in Low Mass X-ray Binaries, due to Roche lobe overflow, and as is expected in Be-star binaries due to accretion from the Be-star disk) around the neutron star, the interaction between the rotating plasma in the accretion disk and the magnetic field of the rotating neutron star determines the rate of angular momentum transport and so the accretion torque.

3.1.1 Disk-Magnetosphere Interaction

The stellar magnetic field has a tendency to penetrate into the disk plasma due to a variety of processes, *e.g.*, Kelvin-Helmholz instability, turbulent diffusion, and reconection to small-scale fields in the disk (Ghosh and Lamb 1979a,b, 1991; hereafter GL). Penetration is actually expected to occur over a considerable part of the disk because the rate of inward radial drift at which the ionized disk plasma can "sweep" the field inward is much slower than the rates of the above processes. Thus, the diamagnetic disk picture, in which the disk is completely excluded from stellar magnetic field (Aly 1980; Kundt & Robnik 1980), is not a self-consistent description of the physical situation.

The precise extent and structure of the disk-magnetosphere interaction region is still a matter of some debate. GL originally described the region in terms of its two conceptually different components: (a) a broad outer transition zone, where magnetic stresses participate in the angular momentum transport, but are not strong enough to cause deviation from Keplerian flow, and, (b) a narrow boundary layer at the inner edge of the disk, where strong magnetic stresses dominate the angular momentum transport, terminate the disk, and channel the accretion flow along the stellar field lines. The location of the inner edge of the disk, r_0, is given by the conservation of angular momentum in the boundary layer,

$$\frac{B_p B_\phi}{4\pi} 4\pi r^2 \delta \simeq \dot{M} r v_K \, . \tag{1}$$

Here, B_p and B_ϕ are respectively the poloidal and toroidal components of the magnetic field, δ is the width of the boundary layer, and v_K is the Keplerian velocity. The value of r_0 obtained in this way, and its scaling with the essential variables $\dot{M}$, μ, and M, depends on the model of the boundary layer, which, in turn, depends on the model of accretion disk appropriate at such radii. For accretion rates and magnetic fields typical of accretion-powered pulsars, the so-called "middle" region of the Shakura-Sunyaev (1973) disk model is appropriate, and the inner radius is given (GL) by

$$r_0 \simeq 1.3 \times 10^8 \dot{M}_{17}^{-46/187} \mu_{30}^{108/187} (M/M_\odot)^{-41/187}$$

Here, $\dot{M}_{17}$ is $\dot{M}$ in units of $10^{17}\mathrm{gs}^{-1}$. Note that the above scalings are close, but not identical, to those of the Alfvén radius for spherical accretion, $r_A = \dot{M}^{-2/7} \mu^{4/7} (2GM)^{-1/7}$.

While GL treated the two above regions separately by semi-analytic or numerical methods, it should be possible to treat the entire region numerically in a unified scheme. Preliminary results of such calculations (Daumerie *et al.* 1993) show that the full region does, indeed, have an outer part where the physical variables change on a lengthscale ~ r, and an inner, boundary-layer like, part where the variables change on a lengthscale ~ $\delta \ll r$. However, the width of the boundary layer is larger than that calculated by GL.

Possible structures of the disk-magnetosphere interaction region which are related to the GL structure, but differ from it in detail, have been discussed qualitatively in recent years. Arons (1987) and coauthors have suggested, for example, that some stellar field lines in the outer parts of the interaction region may become open if the disk plasma loaded on them can be spun up to super Keplerian rotation. A centrifugal wind would then be driven along these field lines. In the picture of Aly and Kuijpers (1990), on the other hand, the interaction region is confined to a thin annular zone where the strength of the stellar magnetic field is ≈ that of the small-scale magnetic fields in the disk (so that reconnection between the two proceeds the most efficiently), and a highly pinched version of the disk extends far into the magnetosphere.

Understanding the electrodynamics of the interaction region is a complicated and challenging task. The stellar magnetic field is wound up in the azimuthal direction and pinched inward in the radial direction by the differential motion between the disk and the star. While it is reasonable to suppose that these distortions are ultimately limited by a variety of processes, *e.g.,* reconnection (GL), flux escape (Wang 1987), and current-driven instabilities, the expected saturation value of the magnetic pitch B_ϕ / B_p in a steady state, and the dominant process that determines this value, are still uncertain. Indeed, the process of buildup and release of magnetic energy is inherently episodic, and the adequacy of a time-averaged description of it in terms of steady-state models may be in question. GL focused on reconnection-limited pitch, and showed that steady-state electrodynamics can then be formulated in terms of an effective elctrical conductivity, assumed isotropic for simplicity. The idea is generally valid, of course, and Campbell (1987) turned it around to calculate the pitches corresponding to simple, mathematically tractable, models of disk conductivity.

3.1.2 Accretion Torque

The accretion torque on the neutron star consists of two parts. The first comes from stresses associated with matter accreting from the inner edge of the disk, and is given by (GL)

$$N_0 \equiv \dot{M}(GMr_0)^{1/2} \, . \tag{3}$$

The second comes from the stresses associated with the magnetic field coupling the star with the disk. The total torque N can be conveniently expressed in terms of N and the dimensionless torque, $n \equiv N/N_0$, depends only on the fastness parameter (GL; EGL),

$$\omega_s \equiv \Omega_s/\Omega_K(r_0) \simeq P^{-1}\dot{M}_{17}^{-3/7}\mu_{30}^{6/7} \, , \tag{4}$$

of the star. Slow rotators ($\omega_s < \omega_c$) are spun up ($n > 0$), while fast rotators ($\omega_s > \omega_c$) are spun down ($n < 0$), by this accretion torque. For $\omega_s > 1$, steady accretion is of course not possible. Here, ω_c is the critical fastness at which the torque changes direction, whose value was found to be ~ 0.3–0.5 in the original GL calculations. A simple analytic approximation to the torque calculated numerically by GL is

$$n(\omega_s) \simeq 1.4 \left(\frac{1 - \omega_s/\omega_c}{1 - \omega_s} \right) . \tag{5}$$

It was suggested by EGL that, due to the balance between stretches of spinup and spindown, the period of a pulsar can be maintained in a range around its critical period, if its luminosity goes through alternate high and low states. This would explain the observability of long-period sources like GX 1+4 and A 0535+26, despite their short spinup timescales in high states. Extensive stretches of spinup and spindown seen in these and other sources since then have borne out this conclusion (also see below).

While the results of subsequent torque calculations using GL-type models (Campbell 1987; Wang 1987; Daumerie *et al.* 1993) have been qualitatively similar, a major issue has been the value of the critical fastness. This parameter depends on the magnetic spindown torque, and so on the magnetic pitch (see above) in the outer parts of the interaction region. GL undoubtedly overestimated the pitch in their approximate treatment of the electrodynamics, so that a more exact calculation should lead to smaller pitches and therefore to larger values of ω_c . However, the extreme value of $\omega_c \simeq 0.97$ obtained by Wang (1987) seems untenable on both theoretical and observational grounds. Wang (a) made an incorrect algebraic approximation, as a result of which the torque diverges as $\omega_s \to 0$, and, (b) neglected screening of the poloidal field. Observationally (see below), there is little evidence for such a large value of ω_c. Indeed, $\omega_c \simeq 0.97$ would imply a tiny range of accretion rates for each pulsar over which spindown could occur (see eq.[4]), making it a rare phenomenon. This is clearly not the case, as most pulsars show spindown, and many of them have long and repeated intervals of it (see above).

3.1.3 Comparison With Observation

Predictions from, accretion torque theories were compared (GL and references therein) with the observed spinup rates of pulsars in the 1970s, as few episodes of spindown were known at the time. The rich structure of spinup/spindown patterns revealed by further observations (see above) makes these comparisons more interesting and complex, and provides more stringent tests of accretion torque models. Observation of spinup and spindown during an outburst of the transient Be-star binary source EXO 2030+375 (Parmar *et al.* 1989) with a pulse period ~ 42 s provided the first opportunity to study the spinup-spindown transition in detail as the luminosity declines and a slow rotator turns into a fast one.

If, as outlined above, both spinup and spindown can be described in terms of a dimensionless torque n which is a function of a dimensionless stellar spin rate ω, alone, this universal scaling (GL) can be demonstrated in the following way. Since $n \propto -\dot{P}P^{-2}L^{-6/7}\mu^{-2/7}$ roughly (as can be shown by combining eqns.[2] and [3]), and $\omega_s \propto P^{-1}L^{-3/7}\mu^{6/7}$, the n vs. ω_s curve can be mapped out from period-luminosity data. Here, L is luminosity of the pulsar. With data on one individual pulsar (μ = constant), we need only plot $-\dot{P}P^{-2}L^{-6/7}$ vs. $P^{-1}L^{-3/7}$. Data on a collection of pulsars can be combined if we have a knowledge of the relative values of μ of these from, say, cyclotron line energies (Nagase 1992; Mihara 1993). I show below the results for two well-studied pulsars.

The ~ 120 s pulsar GX 1+4 with an M6 III giant companion was observed to spin up at a rate $\dot{P}/P \approx -3.10^{-2}$ yr^{-1} in its high-luminosity state in the 1970s (Nagase 1989). It entered an extended low state in the 1980s, from which it reappeared in 1987 in a low-luminosity spindown state (Makishima *et al.* 1988), and has continued to spin down at a rate $P/P \approx 2.10^{-2}$ yr^{-1} upto the BATSE observations. Observations of this source first resolved the dilemma of the short spinup timescales of long-period pulsars (EGL). Shown in Fig. 2a is the observed torque curve for GX 1+4, using a compilation of the long-term period history. A theoretical torque curve given by eqn. (5) with $\omega_c = 0.3$ accounts well for the observations, except perhaps for the highest-fastness point, as Fig.2a shows.

For Her X l, one of the best-studied pulsars ($P = 1.24_{s}$), BATSE data with $\dot{P}$ measured ~ every month (Wilson *et al.* 1993) has been used in Fig. 2b to map out the torque curve for this source from shorter-term period variations, which show spinups and spindowns of comparable maximum strength $|\dot{P}/P| \approx 2.10^{-5}$ yr^{-1} In this case, an additional assumption about the relation between the pulsed, flux (which is what BATSE normally sees) and the total flux is necessary, and I have used a direct proportionality, guided by observations of those sources (*e.g.,* GS 0834 430; C. A. Wilson *et al.*1993) where the latter flux is also available from Earth occultation measurements. The same theoretical curve as in Fig.2a fits these observations, as shown, although other choices of ω_c (see below) are also possible.

These examples are thus consistent with the idea of universal scaling, which implies the same ω_c for both sources. For the two sources above, this yields a relation between their stellar magnetic moments. Using the Her X magnetic field inferred from cyclotron-feature observations (Nagase 1992), this indicates a surface magnetic field ~ 10^{14} G for GX 1+4, in agreement with recent suggestions (Mony *et al.* 1991); proposals have been made for the observation of the corresponding cyclotron feature at ~ 1 MeV with OSSE on CGRO (Prince 1993) or archival HEAO data (Ghosh & Gruber 1994). Finally, note that, although the normaliz - tion constant for the observed ω_s is unspecified in these examples, an *upper bound* on it is implied by the requirement that the maximum observed value of fastness must not exceed unity (see above). The use of this requirement for GX 1+4 leads to $\omega_c \lesssim 0.3$ (Fig.2a). Similar arguments for Her Xl lead to $\omega_c \lesssim 0.6$ (Fig.2b). Thus, spinup/spindown observations suggest a critical fastness of $\omega_c \sim 0.3 - 0.6$.

3.2 *Wind Accretion*

In massive X-ray binaries, if the companion is a supergiant, it drives a strong stellar wind, gravitational capture from which produces accretion on to the neutron star. If the companion is a Be star, the accretion in the quiescent state may be from a similar, weaker wind, and, even during flares due to accretion at a much higher rate from equatorial disks around the Be star, this weak wind may continue to blow from the polar regions of the Be star (Waters & van Kerkwijk 1989, hereafter WK).

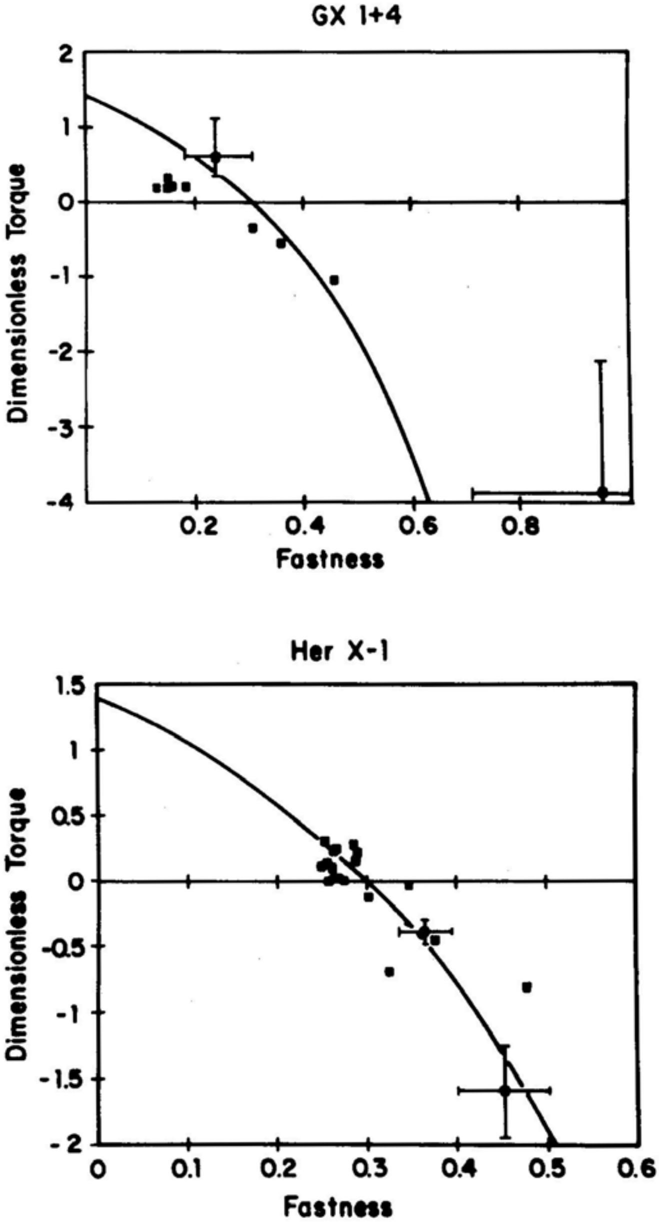

Figure 2: Torque curves for (a) GX 1+4, and, (b) Her Xl. Shown are the dimensionless torque (n) vs. fastness (ω_s) data, superposed on the curve given by eqn.[5] with ω_c = 0.3. Also shown are the typical uncertainties in the observed values, dominated by luminosity variations (see text) during each observation. Such examples support the idea of universal scaling.

3.2.1 Supergiant Systems

The angular momentum transferred to the neutron star per unit mass captured from the wind is usually parameterized in the form $l_\omega = \eta r_a^2 \, \Omega_{orb}$, where $r_a \equiv 2GM/v_0^2$ is the accretion radius, Ω_{orb} is the orbital angular velocity, and η is a dimensionless number. The value of η, which depends on the density and velocity-gradient in the wind, has generally been calculated to be of order unity and both signs by various authors (Shapiro & Lightman 1976; Wang 1981; Anzer *et al.* 1987; Ho 1988). Alternatively, l_ω can be expressed in terms of $r_a v_0$.

Numerical studies of mass capture from stellar winds carried out in recent years (Matsuda *et al.* 1987; Taam & Fryxell 1989; Blondin *et al.* 1990; Matsuda *et al.* 1991, Livio 1993) have shown that the flow patterns often do not approach a steady state; rather, the shock cone oscillates from side to side, producing circulation that reverses quasi-periodically. The origins of this “flip-flop” behavior, which occurs in 2D simulations, but sometimes appears in 3D calculations and sometimes does not, are not fully understood (Livio 1993), even apart from the question of whether numerical artifacts of the simulations, *e.g.,* dimensionality and zoning, are responsible for it. Attempts to attribute it to asymmetries in the upstream flow (Blondin *et al.* 1990) have been in conflict with the result that uniform upstream flows can also develop this behavior when the size of the accreting body is relatively small (Matsuda *et al.* 1991).

The instantaneous magnitude of the specific angular momentum, l_ω, given by these simulations can be $\sim 0.15 r_a v_0$ when a circulating “disk” develops, but its long-term average value is much smaller, as the flow has reversals, accompanied by outbursts of mass flux to the star (Taam & Fryxell 1989). This behavior may be related to the pulse period history of wind-fed HMXBs like Vela X-1, which do indeed show torque reversals on timescales of at least a few days (Deeter *et al.* 1989). However, the typical timescales of reversal given by the current simulations are ~ 1 hr.

3.2.2 Be Star Systems

Accretion from the matter expelled episodically from the Be star in the form of equatorial disks is thought to cause outbursts in these systems. Although more work needs to be done on the formation of accretion disks in such systems, the strong spinup torques observed during outbursts (*e.g.,* in EXO 2030+375) are indirect indications that well-developed accretion disks do form in them.

A useful probe into the spin evolution of these systems is the correlation, $P_{spin} \sim P_{orb}^2$, observed between their spin and orbital periods (Corbet 1986). This has been explained (WK) in terms of the concept of the critical spin period ($\Omega_s = \Omega_c \propto \Omega_K (r_m)$, where r_m is the outer radius of the magnetosphere), at which the net torque on the star vanishes, in analogy with what is done in disk accretion theory (see above). When one uses this concept, radial stellar winds give the (weaker) correlation, $P_{spin} \sim P_{orb}^{4/7}$, observed in wind-fed supergiant systems (WK). However, the observed relation for Be-star systems given above can only be reproduced by dense, equatorial, disk-like flows with a much more gradual velocity law (WK) than the standard radial stellar wind; such winds are now being studied in detail (Bjorkman & Cassinelli 1993).

4. Final Spinup

4.1 *Evolutionary Scenarios*

The final evolution of massive neutron-star binaries (HMXBs) can go in two ways when the common-envelope (CE) phase begins (see vdH92 and references therein). An initially wide binary (*e.g.,* a Be star system) can eject the entire envelope and produce a neutron star with a helium core companion. The system then evolves either (a) by a supernova explosion of the companion, or, (b) by evolution of the companion into a massive white dwarf. In the former case, the chances are high that the system remains bound, producing a double neutron star system like PSR 19134+ 16; if it does become unbound, it produces two single, runaway neutron stars, one recycled and the other newborn. In the latter case, a system like PSR 0655+64 is thought to be produced. On the other hand, an initially narrow binary undergoes a complete spiral-in in the CE phase, producing a Thorne-Zytkow object (vdH92): the envelope is ejected susequently by the flux of energy generated by accretion, leaving behind a single, recycled, neutron star.

The final evolution of low-mass neutron-star binaries (LMXBs) proceeds very differently (see Webbink 1992, 1994 and references therein), in a rather straightforward way. Nuclear evolution of the low-mass companion drives the mass-transfer, ending up with a low-mass helium white dwarf companion to the neutron star, a system like PSR 1953+29.

4.2 *Spin Evolution*

The spin evolution HMXBs is straightforward in principle. In an initially wide system, the neutron star is spun up to short periods (~ 50 – 1000 ms, say) determined by the strength of the full-scale Roche lobe overflow (that initiates the CE phase) and the magnetic field of the neutron star. On the other hand, an initially narrow binary undergoes a complete spiral-in in the CE phase, producing a Thorne-Zytkow object (vdH92) with a disk-accreting neutron star in its core. The end product in this case is a recycled, spun up, single radio pulsar. However, not much work has been done so far on the details of the spin evolution in these cases.

Recent research has mainly focussed instead on the spinup of neutron stars to millisecond periods in LMXBs. Here, the accretion rate is very large (near or at the Eddington rate), and the magnetic field of the neutron star is thought to have become much less (~ 10^8 – 10^9 G), perhaps by the same accretion process (see below, and also Verbunt 1994). A straightforward application of the principles of accretion torques sketched above shows then that recycled pulsars are expected to have spin periods in the observed range of 1 – 100 ms: this was one of the major triumphs of accretion torque theory in the 1980’s. The concept can be displayed pictorially as in Fig.3, which shows the period distribution of recycled spin-powered pulsars superposed on that of the accretion-powered pulsars: *the*

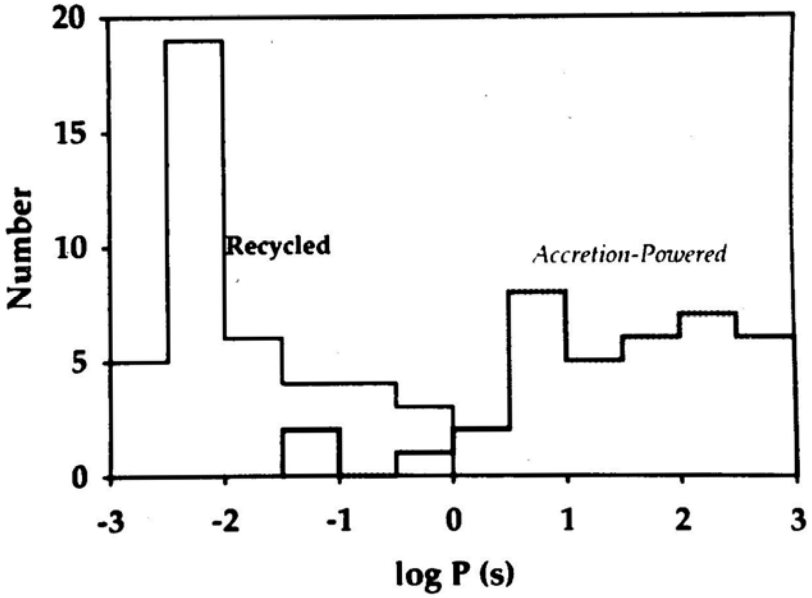

Figure 3: Period distributions of (a) recycled spin-powered pulsars (solid line) and (b) accretion-powered pulsars (shaded line). Included here are all 37 pulsars of the latter category known as of July 1994.

process that moves the latter distribution to the former is the accretion torque that operates during the stage of high mass transfer described above.

4.3 *Magnetic Field Evolution*

A glance at Fig. 1 reveals recycled pulsars are not sacttered all over the bottom left corner of the $B - P$ diagram; rather, they are distributed roughly on a linear band. This agrees very well with the ideas of recycling (see, *e.g.,* White & Stella 1988; Ghosh & Lamb 1992). Indeed, the upper edge of this band is called the "spinup line" (see Bhattacharya & van den Heuvel 1992 for a review), and it represents the shortest period achieved by a pulsar with a given magnetic field during the final spinup process described above. The position of the spinup line gives an excellent diagnostic of the final spinup process, particularly of the state of the inner parts of the accretion disk around the neutron star during this process. It has been shown that this diagnostic can place severe constraints on suggested models of the inner accretion disks in LMXBs (Ghosh & Lamb 1992). Possible models for such disks include the class of cool, one-temperature, optically thick models constructed by Shakura & Sunyaev (1973), and the class of hot, two-temperature, optically thin models constructed by Shapiro *et al.* that the latter class of models is not consistent with observation, although the matter needs to be investigated further (Ghosh & Lamb 1992).

It is also clear from Fig.1 that magnetic fields of neutron stars are reduced

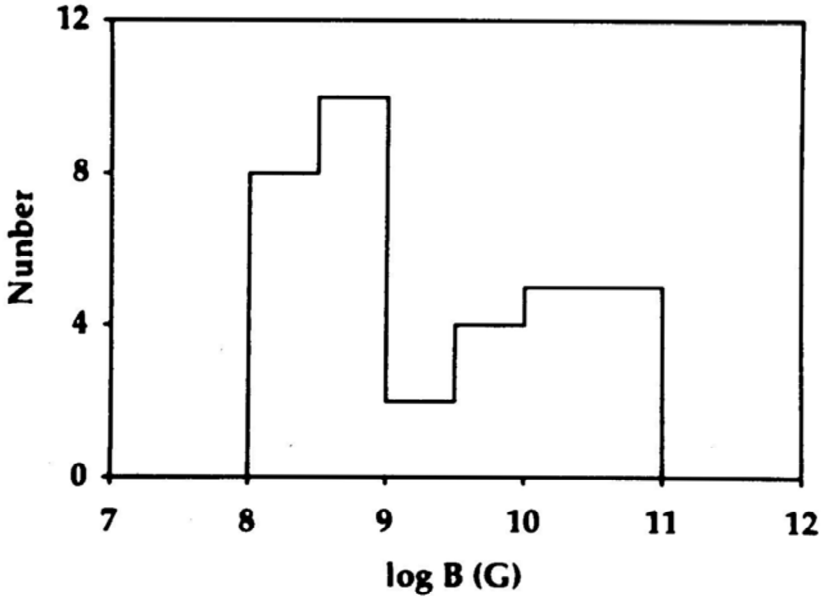

Figure 4: Magnetic field distribution of recycled pulsars. Included are 34 pulsars whose spindown rates have been reliably measured as of July 1994.

considerably during the passage from the accretion-powered phase to the second spin-powered phase. A connection between this magnetic field decay and the accretion during the final spinup phase is obviously possible, and this has been a subject of much study recently (for a review, see Verbunt 1994). I show in Fig.4 the magnetic field distribution of recycled pulsars. (Note that these are uncorrected for the so-called Shklovskii effect described by Camillo . Fig.4: inclusion of this effect does not change any of the conclusions described here.) A bimodal distribution is strongly hinted at (Kulkarni 1992). The pulsars with the lower magnetic fields have low-mass companions in wide, circular orbits (*i.e.*, pulsars of the “1953+29 Class”, vdH92), and are thought to have descended from LMXBs. By contrast, the pulsars with the higher magnetic fields have either neutron star companions in narrow and eccentric orbits, or massive white dwarf companions in narrow orbits (*e.g.*, PSR 0665+64): these are collectively called pulsars of the “1913+16 Class” (vdH92) and are thought to have descended from HMXBs. Why is this so? From the point of view of accretion-induced field decay, an obvious explanation is, of course, that the ~ 10^3 -10^4 yr timescale for the final evolution of HMXBs (vdH92) implies that only a tiny amount of matter has been accreted by the neutron star, while the much longer, ~ 8.10^7 yr, timescale for the final evolution of LMXBs implies a significant amount of accreted matter, typically a few tenths of a solar mass. This has immediate, and quantitative, consequences for the systematics of accretion-induced field decay, which are being keenly pursued at present.

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